2017 DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting

Cummins Electric Truck with Range-Extending Engine (ETREE)

Project ID: GI189

Principal Investigator: John Kresse
Cummins, Inc.
June 7, 2017

"This presentation does not contain any proprietary, confidential, or otherwise restricted information."

Timeline

- Three year project
- Project start date: July 2016
- Project end date: June 2019

Project Goals / Barriers Addressed

- Use electrical grid energy to reduce fuel consumption at least 50% over wide range of drive cycles
- EV-based commercial vehicle with multi-speed transmission that provides equivalent performance and range as conventional vehicle

Budget

Project (overall):	$6,295,281
DOE Share:	$4,126,570
FFRDC:	$355,708
Contractor funding:	$1,813,003
Funding received:	$845,639

Partners

- Prime: Cummins
- Subcontractors
  - PACCAR
  - Argonne National Lab
  - National Renewable Energy Lab
  - The Ohio State University

Relevance of ETREE project

- Two keys to widespread electrified commercial vehicle adoption
  1. For pure EV, battery improvements are needed: cost(↓) & energy capacity(↑)
  2. Must overcome fleet operator risk (purchase, operational)
- In the near- to medium-term, solved by: a PHEV w/ low-cost range extender
  - Proven to work over wide variety of missions & environmental conditions
  - Manufactured, serviced, certified, delivered, integrated using standard commercial vehicle processes
- Vehicle developed in this project can be considered a prototype for a commercially viable heavily electrified commercial vehicle
- ETREE will deliver equivalent continuous performance (transmission output torque and power) and range as conventional class 6 truck

EV – electric vehicle PHEV – plug-in electric vehicle

Specific Objectives

- Using electrification, improve the Kenworth K270 / Peterbilt 220 to substantially reduce fuel consumption for the **class 6 pickup & delivery market** while meeting all requirements of the existing trucks

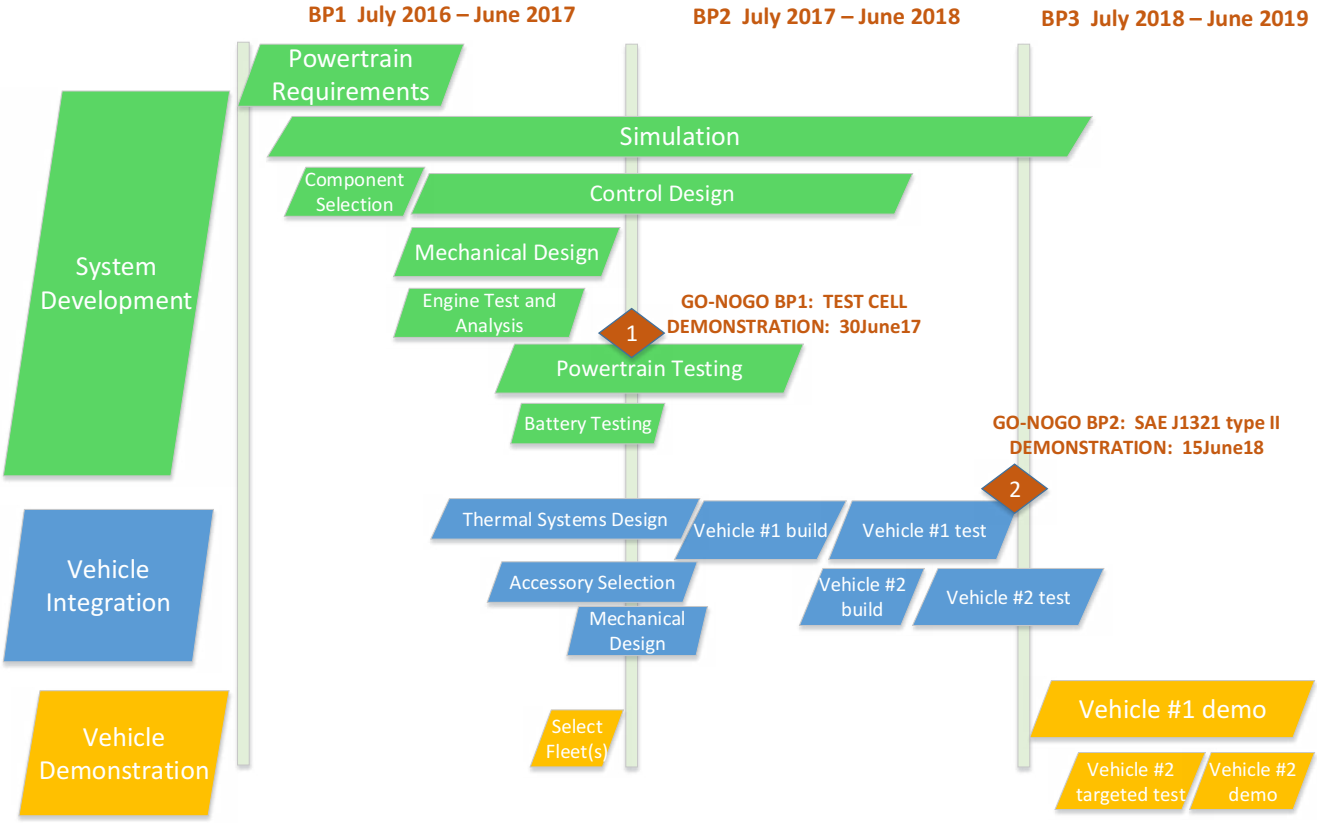
- Investigate the potential to improve a commercial EV using:
  - range extending engine / generator
  - multi-speed transmission
  - electronic braking system
- Develop hybrid system controls technology focused on battery state-of-charge trajectory management and vehicle integration (electrified accessories, thermal management) systems

Program Milestones

Budget Period 1

Milestone	Description	Delivery Date	Status
M1	Technical Profile & Component Requirements	9/10/2016	Complete; 9/15/2016
M2	Procurement Requirements Complete	9/30/2016	Complete; 11/10/2016
M3	ICE Hardware Optimization Complete	2/19/2017	Complete; 12/05/2016
M4	Range Extender & Powertrain Operational in Test Cell	4/7/2017	
GNG1	Design Reviews Complete; Fuel Consumption Reduction Objectives Achieved	6/30/2017	

Approach / Plan



Technical Progress

Identification of drive cycles by NREL

Drive and Duty Cycle Analysis

Define Operational Modes

Representative Cycle Creation

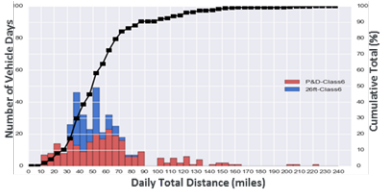
Model Based Validation

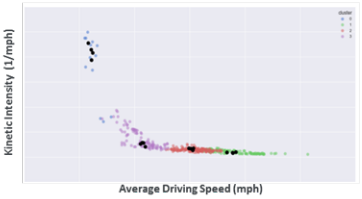
Testing

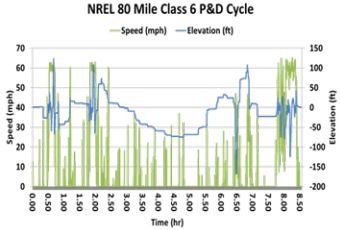
Fleet DNA Project

DRIVE Analysis Tool

AUTONOMIE



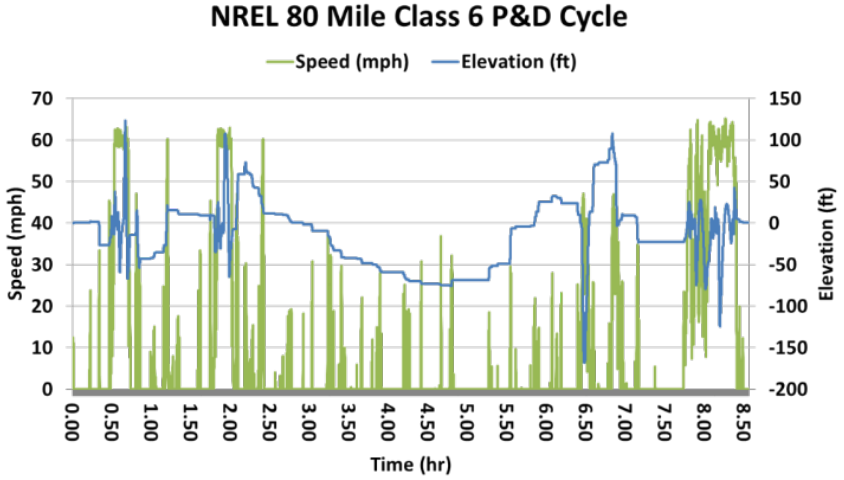




Technical Progress

NREL 80 and NREL 100 representative drive cycles

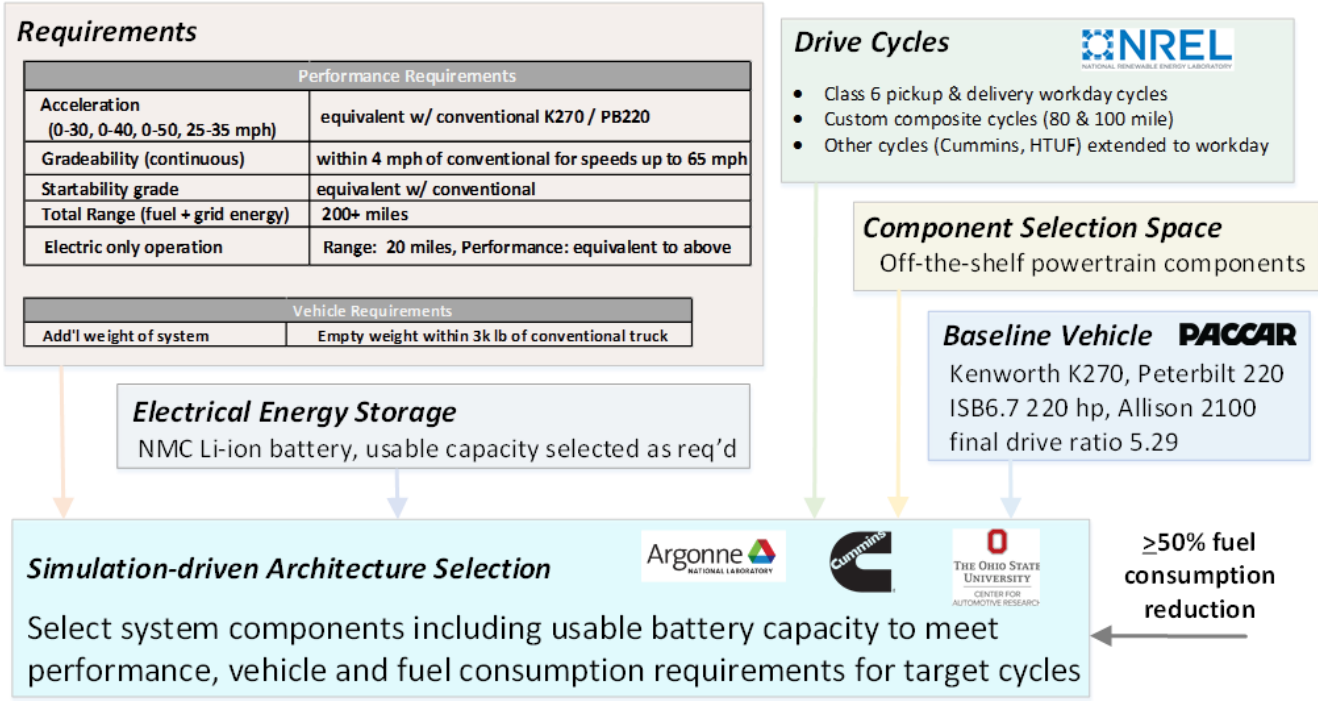
- For analysis, electric vehicles require use of a workday drive cycle
  - Due to limited energy density and impact of state-of-charge on continuous power
- New NREL 80 and NREL 100 pickup and delivery cycles
  - **NREL 80 selected as the ETREE target cycle**; represents 80th percentile of required energy of representative drive cycles



- Cycles include grade, key status
- See backup slide for comparison of metrics to existing standard test cycles

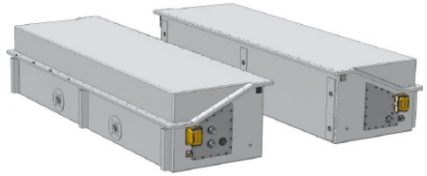
Technical Progress

Simulation-focused component selection

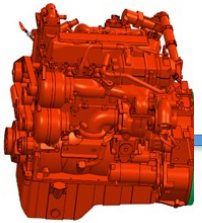


Technical Progress

Series hybrid architecture with 112 kW-h energy storage



112 kW-h NMC Li-ion battery



damper

130 kW PM generator

~/-

-/~

160 kW PM traction motor

Allison 3000 ETREE transmission

Transmission input stop-start system

700 V DC bus nominal

155 kW ISB4.5 with DPF, SCR, DOC aftertreatment

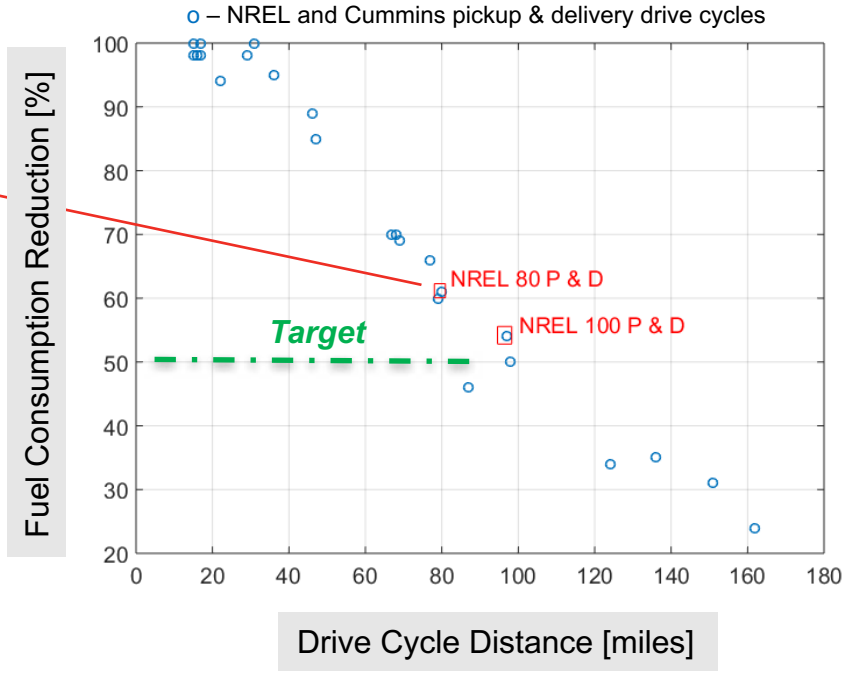
DPF – diesel particulate filter
SCR – selective catalytic reduction
DOC – diesel oxidation catalyst
NMC – nickel manganese cobalt

Permanent magnet (PM) electric machines with listed continuous ratings

Technical Progress

Predicted fuel consumption reduction -

Predicted fuel consumption for target cycle (NREL 80) is well within objective.

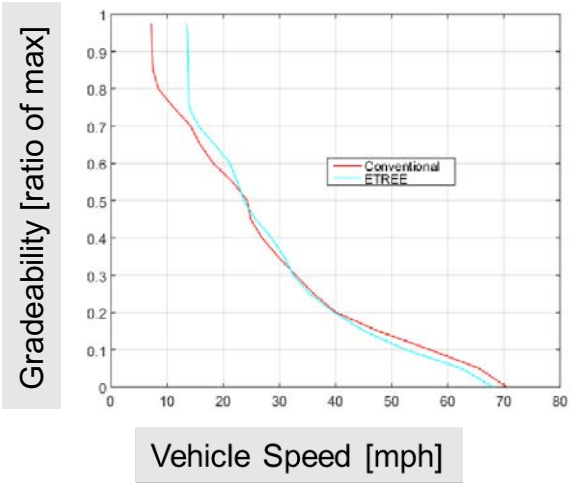


Technical Progress

Predicted performance

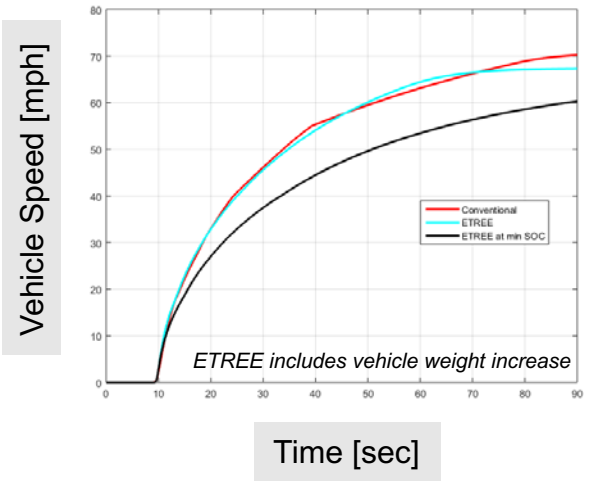
EV-only range	40 miles
Total range	270 miles

ambient temperature impact TBD



Acceleration Performance (level ground)

- At minimum battery state-of-charge (SOC), performance on level grade is still marginally acceptable due to generator size (130 kW)



Technical Progress

State-of-Charge (SOC) trajectory optimization

Optimization problem to help design range extender operation

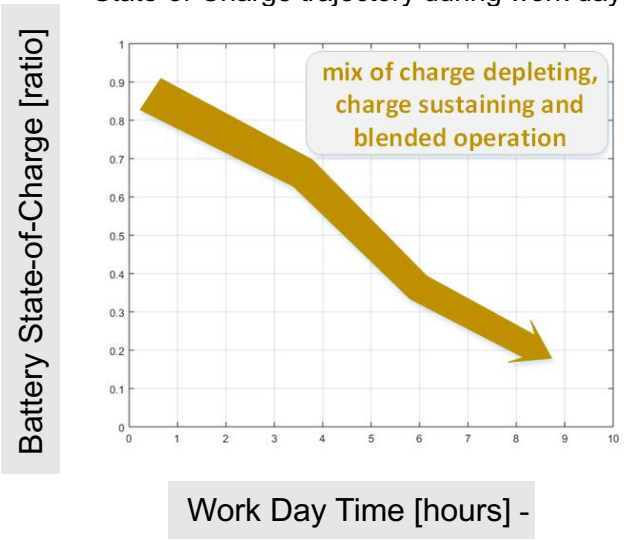
Cost function

- Reduce fuel consumption
- Increase battery life
- Manage aftertreatment temp.
- Meet performance metrics

Noise factors

- Work day time
- Drive cycle variation
- Vehicle weight
- Ambient temperature

State-of-Charge trajectory during work day

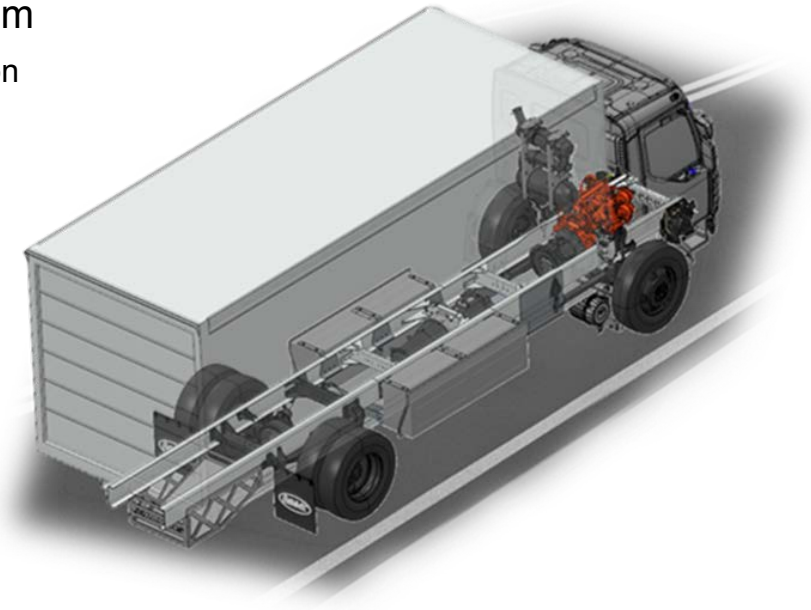


Technical Progress

Vehicle design and integration

- J1772 level 2 EVSE support
- Electronic Braking System
  - Includes blending of traction motor energy with brakes
- Electrified accessories
- Thermal management systems
- Passively cooled battery

K270/PB220 ETREE

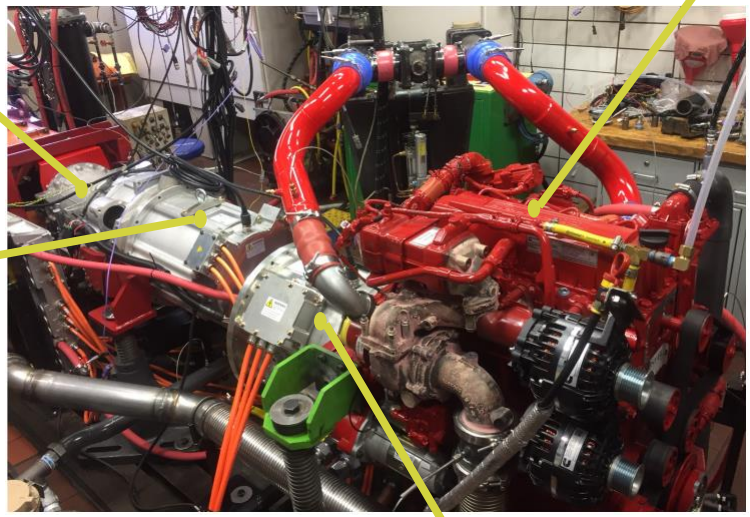


EVSE - Electric vehicle supply equipment

Technical Progress

Test cell testing

- Budget Period 1 GO/NO-GO: demonstrate 50% fuel consumption reduction objective in test cell on target cycle



Not shown:
250 kW battery emulator, engine aftertreatment

Remaining Challenges & Future Research

- Continue vehicle integration tasks & vehicle build
  - Integrate and implement thermal management systems in vehicle
- Continue test cell testing for Q2/3 2017
- Vehicle 1
  - At Cummins
  - TRC* test track J1321 Type II (6/2018)
    - Budget Period 2 Go/no-go milestone
  - Fleet operator (8/2018 - 7/2019)
- Vehicle 2
  - Targeted testing (cold, hot, grades)
  - PACCAR Technical Center

(1)

(2)

(4)

(3)

*TRC – Transportation Research Center

1, 4. Courtesy of Transportation Research Center Inc.

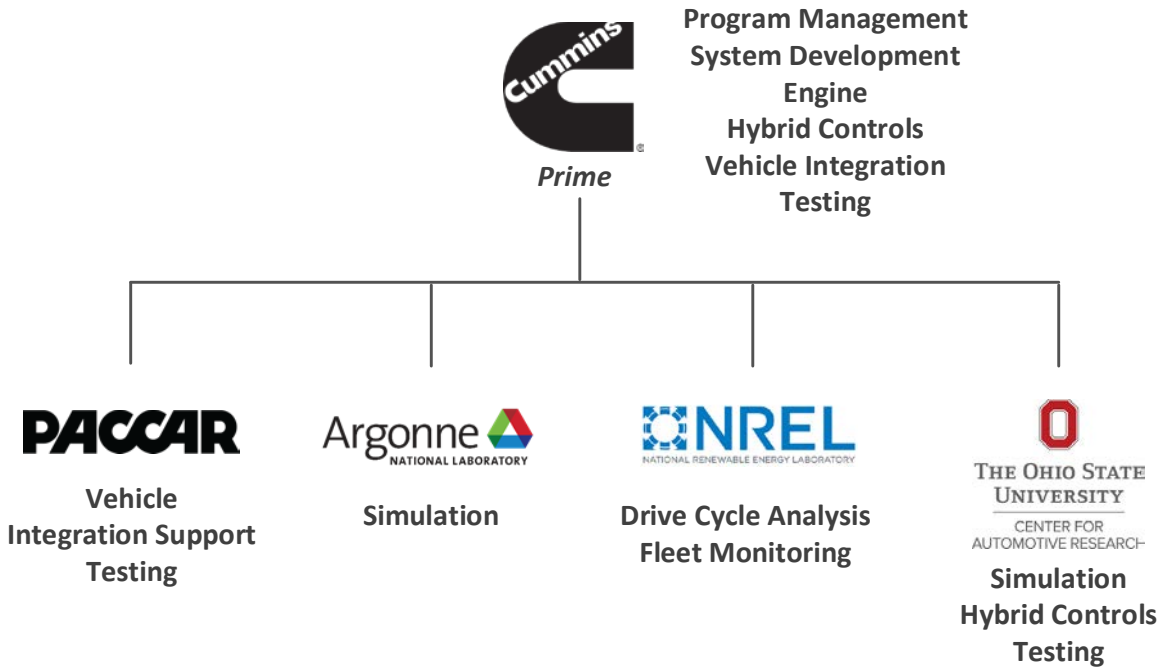
2, 3. Courtesy of PACCAR Inc.

"Any proposed future work is subject to change based on funding levels."

Response to Previous Comments

- Project is new; started in July 2016.

Team


Cummins
Prime
Program Management
System Development
Engine
Hybrid Controls
Vehicle Integration
Testing
PACCAR
Vehicle
Integration Support
Testing
Argonne
NATIONAL LABORATORY
Simulation
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Drive Cycle Analysis
Fleet Monitoring
THE OHIO STATE UNIVERSITY
CENTER FOR AUTOMOTIVE RESEARCH
Simulation
Hybrid Controls
Testing

Summary

- Team has developed an electrified powertrain capable of meeting the project objectives
  - At least 50% fuel consumption reduction for a wide range of class 6 pickup and delivery drive cycles
  - Comparable performance to conventional Kenworth K270
- NREL has developed composite work day drive cycles using relevant real-world data from Fleet DNA for defining/testing performance requirements of electrified commercial vehicles
- Test cell testing of powertrain is progressing to meet first year go / no-go milestone
- Vehicle integration is focus of upcoming budget period 2

Thank you.

Technical Backup Slides

NREL 80 and 100 Drive Cycles

Comparison to existing drive cycles

	NREL_80	NREL_100	NYC COMP	HTUF Class 6 PDDS	CSHVC (CSC)	CARB HHDDT	CARB HHDDT 65
duration (hrs)	8.56	10.77	0.29	1.09	0.47	1.00	1.00
maximum driving speed (mph)	65.09	64.73	36.00	56.60	43.80	59.30	67.10
average driving speed (speed > 0, mph)	31.86	30.34	13.11	21.95	18.44	35.59	42.16
standard deviation of speed (mph)	18.68	18.40	9.47	13.39	13.06	24.48	28.77
maximum acceleration (ft/s/s)	7.18	8.73	6.79	2.93	3.81	4.25	6.60
maximum deceleration (ft/s/s)	-7.56	-10.22	-6.42	-4.99	-5.87	-4.06	-9.39
average acceleration (ft/s/s)	1.07	1.06	1.51	1.64	1.31	0.52	0.71
average deceleration (ft/s/s)	-1.14	-1.08	-1.71	-2.06	-1.58	-0.58	-0.78
acceleration events per mile	5.10	6.29	57.88	11.01	20.06	6.53	13.18
deceleration events per mile	5.10	6.29	54.68	13.21	20.06	6.83	12.54
number of stops per mile	1.45	1.34	7.98	2.57	1.95	0.50	0.37
characteristic acceleration (ft/s/s)	0.41	0.40	0.75	0.58	0.56	0.18	0.16
aerodynamic speed (ft/s)	73.13	72.82	30.40	44.28	40.66	74.36	87.33
kinetic intensity (1/mile)	0.41	0.40	4.30	1.55	1.79	0.17	0.11

Data courtesy of Adam Duran of NREL

Battery size will determine the fraction of real world cycles where 50% fuel is saved

This is a trade off between fuel savings & cost

- 20 Class 6 P&D representative cycles from FleetDNA shows that 110kWh pack achieves more than 50% fuel savings in 84% of the cycles.
- Remaining 16% of the cycles need a much larger battery to achieve the same goal.

Battery size	% of cases where 50% fuel is saved
80 kWh	68%
100 kWh	73%
110 kWh	84%
125 kWh	84%

Slide courtesy of Ram Vijayagopal of Argonne National Lab